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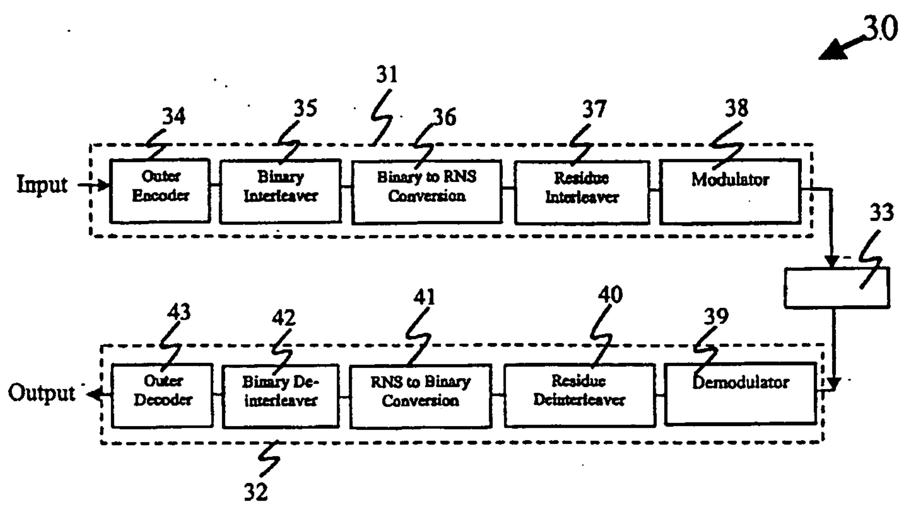
(54) Title: COMMUNICATION SYSTEM USING A MODULATION METHOD BASED ON RESIDUE NUMBER SYSTEMS



(57) Abstract: A communication system (30) having a transmitting section (31) and a receiving section (32) to transmit and to receive, respectively, a spread signal. The communication system (30) applies a modulation scheme using the residue number system to modulate binary information for the spread signal using a modulator (38) of the transmitting section (31). Residue sets are derived from a plurality of bits provided by the binary information. Each residue set corresponds to a residue symbol and has at least one non-redundant residue. A fixed number of least significant binary bits of each residue set are then modulated to form a modulated symbol. An orthogonal code sequence, associated with remaining bits of the binary bits of each residue set, is then selected to spread the modulated symbol on a residue channel for transmission. At the receiving section (32), a demodulator (39) demodulates the spread signal to obtain the binary information.

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COMMUNICATION SYSTEM USING A MODULATION METHOD BASED ON RESIDUE NUMBER SYSTEMS

Field of the Invention

The present invention relates to modulation methods used in communication systems. More particularly, the present invention relates to a communication system using a modulation method based on residue number systems to thereby improve bandwidth efficiency.

Background

In code-division multiple access (CDMA) systems, multiple usage at the same time causes multiple access interference (MAI). Consequently, MAI limits the capacity and the performance of such systems as communications between users are adversely affected by undesired interferences. A solution to reduce MAI in such CDMA systems is obtained by applying M-ary orthogonal signaling. Generally, M-ary orthogonal signaling provides a set of orthogonal functions to represent a set of symbols used for transmission.

M-ary orthogonal-based systems have been proposed in the art. For example, U.S. Patent Number 5,103,459, issued to Gilhousen et al on 7th April 1992 and assigned to Qualcomm Incorporated, describes a system in which a base station spreads data signals destined for different mobile stations by mutually orthogonal codes, while each mobile station uses all of the orthogonal codes for M-ary encoding of data to be transmitted to the base station.

Recently, as specified in TIA/EIA/IS-95 Interim Standard (July 1993) entitled "Mobile station – Base station compatibility standard for dual mode wideband spread spectrum cellular system", the Telecommunication Industry Association (TIA) has adopted M-ary orthogonal-based signaling using Walsh functions in direct sequence CDMA (DS-CDMA) systems as a standard. In an M-ary orthogonal-based system, k

data bits are mapped into one of M $(=2^k)$ Walsh functions having fixed durations. A transmitter and a receiver of an M-ary orthogonal-based system are respectively illustrated in FIGs. 1 and 2.

At the transmitter, information bits are first modulated using a Walsh-Hadamard modulator. The resulting signal is scrambled using a user's long code and then separately multiplied in both I and Q channels by short pseudo-random noise (PN) codes to derive spread signals. The spread signals are then up-converted to radio frequency (RF) signals for transmission.

M-ary orthogonal signaling is typically used for uplinking transmissions from a mobile communication unit to a base station. The mobile communication unit operates within a mobile communication environment that disperses transmitted signals through different physical paths. The mobile communication environment therefore provides a multipath environment for the transmitted signals. A receiver of the base station receives multipath signals corresponding to transmitted signals from all users. Thus, signals received at the receiver from the multipath environment are the sum of such multipath signals and noise.

The multipath components of a transmitted signal are independent due to considerable path delays that can extend to a few microseconds. Consequently, time diversity due to independent multipath delay components of the transmitted signal can be exploited by appropriate processing components at the receiver. A RAKE receiver is an example of a receiver that exploits this time diversity by collecting and combining energy from the multipath signals. The RAKE receiver has a receiver finger for each multipath signal component. After descrambling, a received signal is correlated by a despreading code in each RAKE finger, which is time aligned with the delay component of a multipath signal. This is done using all possible orthogonal codes having the same processing gain such as Walsh-Hadamard codes. After despreading, signals corresponding to the same despreading code are combined. The receiver uses a maximum likelihood decision rule. With this method, a despread

variable with maximum amplitude is selected. The index of the largest despread variable denotes the transmitted symbol.

M-ary signaling uses symbol-by-symbol spreading and despreading. As such, more bits are processed for a given processing cycle than bit by bit processing of conventional methods and this thereby improves bandwidth efficiency. The bandwidth efficiency in the M-ary orthogonal-based system is also improved by increasing the number of bits per symbol. However, increasing the number of bits per symbol (k) increases spreading factor and this, unfortunately, exponentially increases the number of correlators or matched filters required at the receiver. Hence, to simplify a receiver that would otherwise require an undesirable number of correlators or matched filters, the length of transmitted bits/symbol needs to be limited. For example, to receive a transmitted symbol having 16 bits per symbol that is transmitted from a set of 2^{16} (=65536) orthogonal codes, the receiver requires 2^{16} correlators or matched filters. In addition, the receiver has to simultaneously acquire and track 65536 spread codes and this is not practical for existing mobiles and base stations.

On the other hand, bandwidth efficiency can be enhanced by multi-coded CDMA systems, in which data bits are transmitted in parallel using orthogonal spread codes. However, increasing the number of bits per symbol also increases the number of parallel channels and this undesirably increases the likelihood of signal interferences of a desired signal by undesired signals in a multi-path environment. Such signal interferences are more severe in a multi-user environment.

Considering the problem of complexity of receivers in M-ary orthogonal-based systems due to an increase in the number of bits per symbol, L. L. Yang and L. Hanzo proposed an alternative method of modulating information bits that uses a residue number system (RNS). ("Performance of a residue number system based DS-CDMA over multipath channel using orthogonal sequences" by L. L. Yang and L. Hanzo , European Transactions on Communications, Vol. 9, No. 6, Nov-Dec 1998,

pp. 525-536.) In this alternative method, any information symbol X to be transmitted, can be uniquely and unambiguously represented as:

a set of residues: $X=\{r_1, r_2, \ldots r_u\}$

with respect to a set of moduli $\{m_1, m_2, \ldots m_u\}$,

where $r_i = rem(X,m_i)$ for $i = 1$ to u, $rem(x,y)$ being the remainder of x with respect to y, provided X is less than the product of all moduli.

The elements of the moduli set should be pair-wise relatively prime. The product of all moduli provides a dynamic range and determines the maximum number of bits possible in a symbol. The residues are mapped into a set of orthogonal sequences and are transmitted in parallel. Operations on individual residue channels are mutually independent due to the carry-free nature of residue arithmetic. Also, some residue digits can be discarded without affecting the result, provided a sufficient number of residue digits are retained for the reconstruction of the symbol. These RNS properties are exploited further by introducing redundant moduli for the enhancement of system performance in an RNS-based CDMA system.

Inserting redundant moduli can enhance error detection and/or correction properties for RNS. A redundant residue number system (RRNS) is obtained by appending v-u pair-wise relatively prime moduli to the non-redundant moduli. The redundant moduli should obey the condition $\{m_{u+1},..m_v\} > max\{ m_1, m_2, \ldots m_u\}$. The error detection and correction properties of RNS are well established. In general, v-u redundant moduli can detect v-u errors and can correct up to $(v-u)/2$ errors. These fault tolerant features are suitable for communication systems in which performance is severely limited by channel conditions, such as multipath interference, multiple access interference and various other channel noise conditions.

Even though it is possible to increase bandwidth efficiency of an M-ary orthogonal based DS-CDMA system by increasing the number of bits per symbol, the complexity required by a receiver of such a system increases linearly with M and exponentially with the number of bits per symbol. Consequently, both the maximum

number of orthogonal sequences and an acceptable complexity of the receiver limit achievable bandwidth efficiency of such a system. Hence, the maximum possible data transfer rate is also limited. On the other hand, the number of parallel channels used and, correspondingly, the maximum possible data transfer rate limits the performance of existing multi-coded CDMA systems. Also, the average performance of existing multi-coded CDMA systems is inferior to a normal M-ary orthogonal based DS-CDMA system of equal data rate due to a higher presence of MAI. Using residue number representation, the number of orthogonal codes required for transmission can be reduced from M $(=2^k)$ to the sum of all moduli, which is much less. This therefore reduces the number of correlators or matched filters and, hence, achieves a reduction in computational complexity at the receiver. Unlike existing multi-coded CDMA systems, the number of parallel channels required for transmission remains the same (that is, equals the number of residues used) irrespective of the number of bits per symbol. However, the RNS-CDMA system proposed by Yang and Hanzo does not fully exploit the potential of maximum bandwidth efficiency using orthogonal modulation in which residue values are directly mapped onto orthogonal spread codes without any modification and all the orthogonal spread codes corresponding to a symbol are transmitted in parallel.

Furthermore, in multicarrier modulation systems, an entire channel is divided into many narrow band sub-channels via which a spread signal is transmitted in parallel. Consequently, duration of symbols encoded within the spread signal increases. This is significant in high data rate transmission where the ability to achieve higher bit rates at lower error rates is limited by the propagation characteristics of a wireless communication environment such as inter-symbol interference due to large delay spread of different receiving paths and fast fading caused by vehicular movement. The performance in multicarrier modulation systems is thus comparable to narrow band radio frequency channel due to frequency non-selective fading in sub-carriers. To overcome this and to reduce the bit error rates, a combination of multicarrier modulation systems and CDMA is proposed in prior art communication systems. In such systems, the energy of each information symbol is

spread over several sub-carriers, which leads to a diversity gain in a broadband-fading channel. Moreover, a spread signal can be transmitted and received using a fast Fourier transform (FFT) device without increasing transmitter or receiver complexity. As such, a multicarrier CDMA system is potentially robust to channel frequency selectivity with good frequency utilization efficiency. However, the symbol rate in each sub-carrier of such a system is reduced to allow longer symbol duration which is easier to quasi-synchronize spread signals. Such reduction of the symbol rate adversely affects bandwidth efficiency.

In view of the above limitations to existing multi-coded or RNS-based CDMA systems, a need clearly exists for a modulation method to further improve bandwidth efficiency in existing RNS-based CDMA systems.

Summary

In accordance with one aspect of the invention, there is disclosed a method for modulating a binary input signal to form a spread signal for transmission, the method comprising the steps of:

deriving one or more residue sets from a plurality of bits provided by the binary input signal, each of the residue sets having one or more residues, corresponding to a residue symbol, and having at least one non-redundant residue;

converting each of the residues to binary bits;

modulating one or more least significant bits of the binary bits to form a modulated symbol for each of the residues;

selecting an orthogonal code sequence associated with remaining bits of the binary bits for each of the residues;

and

spreading the modulated symbol for each of the residues using the selected orthogonal code sequence to form a residue channel for each of the residues for transmission.

Generally, the converting step can comprise the step of grouping the residue sets to form a symbol frame.

More generally, the converting step can further comprise the step of interleaving the residues from the symbol frame to form an interleaved residue frame.

Yet more generally, the interleaving step can comprise the step of arranging the residues based upon an interleaving depth of the interleaved residue frame and the number of the residue channel.

Still more generally, the arranging step can comprise the step of setting the interleaving depth based upon the number of the one or more residue sets.

Optionally, the method can further comprise the step of combining output from each residue channel to form the spread signal.

Generally, the combining step can be carried out in parallel.

Alternatively, the combining step can comprise the step of serially concatenating the output.

More optionally, the method can further comprise the step of scrambling the spread signal using a predetermined scrambling code.

Generally, the method can further comprise the steps of:

converting the spread signal to parallel outputs;

and

inverse Fast Fourier transforming the parallel outputs to form transformed outputs.

More generally, the converting step can comprise the step of interleaving the spread signal.

Yet more generally, the method can further comprise the step of scrambling the spread signal using a predetermined scrambling code prior to the converting step.

Still more generally, the method can further comprise the step of inserting a guard interval between the transformed outputs prior to transmission.

In accordance with another aspect of the invention, there is disclosed a method for demodulating a spread signal received within a communication environment, the method comprising the steps of:

despreading the spread signal with one or more code sequences associated with each of at least one residue channel to determine a code sequence, the code sequence being associated with one or more most significant bits and used for transmitting the spread signal for each residue channel;

demodulating despread output corresponding to the determined code sequence to form an estimated modulated symbol and subsequently derive one or more least significant bits for the each of at least one residue channel;

combining the one or more most significant bits and the one or more least significant bits to form a residue associated with each residue channel;

and

deriving a binary output signal from one or more residue symbols, each of the one or more residue symbols being based upon a plurality of residues associated with the at least one residue channel, the plurality of residues corresponding to one or more residue sets.

Generally, the despreading step can comprise the step of applying a ratio static test on each of the despread output to obtain test statistics for each of the one or more residues.

More generally, the deriving step can comprise the step of choosing non-redundant residues for each of the one or more residue sets based on corresponding the test statistics for each of the one or more residues.

Optionally, the despreading step can comprise the step of estimating channel status information associated with each residue channel.

More optionally, the despreading step can comprise the step of the demodulating step comprises the step of forming the estimated modulated symbol using the despread output of selected spread code and estimated channel status information associated with the each of at least one residue channel.

Generally, the method can further comprise the step of forming an interleaved residue frame from the plurality of residues.

More generally, the forming step can comprise the step of deinterleaving the interleaved residue frame to form a symbol frame, the symbol frame having one or more residue sets based upon the plurality of residues, each of the residue sets representing a symbol.

Yet more generally, the deinterleaving step can further comprise the step of setting an interleaved depth for the interleaved residue frame based upon the number of the one or more residue sets.

Optionally, the method can further comprise the step of descrambling the spread signal using a predetermined scrambling code.

Generally, the method can further comprise the steps of:

converting the spread signal to parallel outputs;

and

Fast Fourier transforming the parallel outputs to form transformed outputs.

More generally, the method can further comprise the step of descrambling the spread signal using a predetermined scrambling code prior to the converting step.

Optionally, the converting step can comprise the step of deinterleaving the spread signal.

In accordance with yet another aspect of the invention, there is disclosed a communication system having a transmitting section for modulating a binary input signal to form a spread signal for transmission, the communication system comprising:

means for deriving one or more residue sets from a plurality of bits provided by the binary input signal, each of the residue sets having one or more residues, corresponding to a residue symbol, and having at least one non-redundant residue;

means for converting each of the residues to binary bits;

means for modulating one or more least significant bits of the binary bits to form a modulated symbol for each of the residues;

means for selecting an orthogonal code sequence associated with remaining bits of the binary bits for each of the residues;

and

means for spreading the modulated symbol for each of the residues using the selected orthogonal code sequence to form a residue channel for each of the residues for transmission.

Generally, the converting means can comprise means for grouping the residue sets to form a symbol frame.

More generally, the converting means can further comprise means for interleaving the residues from the symbol frame to form an interleaved residue frame.

Yet more generally, the interleaving means can comprise means for arranging the residues based upon an interleaving depth of the interleaved residue frame and the number of the residue channel.

Still more generally, the arranging means can comprise means for setting the interleaving depth based upon the number of the one or more residue sets.

Optionally, the communication system can further comprise means for combining output from each residue channel to form the spread signal.

Generally, the combining means can comprise means for carrying out the combining in parallel.

Alternatively, the combining means can comprise means for serially concatenating the output.

More optionally, the communication system can further comprise means for scrambling the spread signal using a predetermined scrambling code.

Generally, the communication system can further comprise:

means for converting the spread signal to parallel outputs; and

means for inverse Fast Fourier transforming the parallel outputs to form transformed outputs.

More generally, the converting means can comprise means for interleaving the spread signal.

Yet more generally, the communication system can further comprise means for scrambling the spread signal using a predetermined scrambling code prior to the converting.

Still more generally, the communication system can further comprise means for inserting a guard interval between the transformed outputs prior to transmission.

In accordance with a further aspect of the invention, there is disclosed a communication system having a receiving section for demodulating a spread signal received within a communication environment, the communication system comprising:

means for despreading the spread signal with one or more code sequences associated with each of at least one residue channel to determine a code sequence, the code sequence being associated with one or more most significant bits and used for transmitting the spread signal for each residue channel;

means for demodulating despread output corresponding to the determined code sequence to form estimated modulated symbol and subsequently derive one or more least significant bits for each residue channel;

means for combining the one or more most significant bits and the one or more least significant bits to form a residue associated with each residue channel;

and

means for deriving a binary output signal from one or more residue symbols, each of the one or more residue symbols being based upon a plurality of residues associated with the at least one residue channel, the plurality of residues corresponding to one or more residue sets.

Generally, the despreading means can comprise means for applying a ratio static test on each of the despread output to obtain test statistics for each of the one or more residues.

More generally, the deriving means can comprise means for choosing non-redundant residues for each of the one or more residue sets based on corresponding the test statistics for each of the one or more residues.

Optionally, the despreading means can comprise means for estimating channel status information associated with each residue channel.

More optionally, the demodulating means can comprise means for forming the estimated modulated symbol using the despread output of selected spread code and estimated channel status information associated with the each of at least one residue channel.

Generally, the communication system can further comprise means for forming an interleaved residue frame from the plurality of residues.

More generally, the forming means can comprise means for deinterleaving the interleaved residue frame to form a symbol frame, the symbol frame having one or more residue sets based upon the plurality of residues, each of the residue sets representing a symbol.

Yet more generally, the deinterleaving means can comprise means for setting an interleaved depth for the interleaved residue frame based upon the number of the residue sets.

Optionally, the communication system can further comprise means for descrambling the spread signal using a predetermined scrambling code.

Generally, the communication system can further comprise:

means for converting the spread signal to parallel outputs; and

means for Fast Fourier transforming the parallel outputs to form transformed outputs.

More generally, the communication system can further comprise means for descrambling the spread signal using a predetermined scrambling code prior to the converting.

Optionally, the converting means can comprise means for deinterleaving the spread signal.

Brief Description of the Drawings

Preferred embodiments of the invention are described hereinafter with reference to the drawings, in which:

FIG. 1 is a general block diagram of a prior art transmitter; and

FIG. 2 is a general block diagram of a prior art receiver.

FIG. 3 is a general block diagram illustrating a communication system having a transmitting section and a receiving section in accordance with a preferred embodiment of the invention;

FIG. 4 is a general block diagram illustrating a part of the transmitting section of FIG. 3;

FIGS. 5(a) and 5(b) illustrate an example of an interleaving pattern of a residue interleaver of the communication system of FIG. 3;

FIG. 6 is a general block diagram of a sub-modulator of an n^{th} residue channel of the modulator of FIG. 4;

FIG. 7 is a general block diagram illustrating a part of the receiving section of FIG. 3;

FIG. 8 is a general block diagram of a sub-demodulator of an n^{th} residue channel of the demodulator of FIG. 7;

FIG. 9 is a general block diagram illustrating a spread code selection and ratio statistic measurement module within the sub-demodulator of FIG. 8;

FIG. 10 is a general block diagram of a correlator bank for an n^{th} path of the spread code selection module of FIG. 9;

FIG. 11 is a general flow chart of a method for modulating based on residue number systems by the communication system of FIG. 3;

FIG. 12 is a general flow chart of a method for demodulating based on residue number systems by the communication system of FIG. 3;

FIG. 13 is a comparative graph of minimum spreading factor required with number of bits per symbol in the communication system of FIG. 3 and prior art systems;

FIG. 14 is a comparative graph of computational complexities in the communication system of FIG. 3 and prior art systems;

FIG. 15(a) is a comparative graph of performance of the communication system of FIG. 3 for parallel representation of residue channels and a processing gain of 64 in a Rayleigh fading channel of 16 bits/symbol and a moduli set;

FIG. 15(b) is a comparative graph of performance of the communication system of FIG. 3 for serial concatenation of residue codes and a processing gain of 16*5 in the Rayleigh fading channel of FIG. 13a;

FIG. 16 is a comparative graph of performance of the communication system of FIG. 3 with alternative modulation methods based upon a processing gain of 256 and a Rayleigh fading channel of 16 bits/symbol and yet another moduli set;

FIG. 17 is a comparative graph of performance of the communication system of FIG. 3 with alternative modulation methods based upon a reduced processing gain of 64 and differing channel bits/symbol and moduli sets;

FIG. 18 is a general block diagram illustrating a part of the transmitting section of FIG. 3 in accordance with an alternate embodiment of the invention;

FIG. 19 is a general block diagram illustrating a part of the receiving section of FIG. 3 in accordance with the alternate embodiment of the invention;

and

FIG. 20 is a general block diagram of a sub-demodulator of an n^{th} residue channel of a demodulator of the alternate embodiment.

Detailed Description

A communication system, a modulation method and a demodulation method based on residue number system (RNS) for the communication system are described in accordance with preferred embodiments of the invention. In the following, numerous details are provided for a more thorough description. It shall be apparent to one skilled in the art, however, that the invention may be practiced without such details. In other instances, well-known details have not been described at length so as not to obscure the invention.

The advantages of the preferred embodiments of the invention are manifold. One advantage of the preferred embodiments of the invention is that a lesser

spreading factor is required compared to existing residue number system (RNS) code-division multiple access (CDMA) systems of the same capacity. Thus, since bits per symbol can be increased without changing spreading factor, considerable improvement in bandwidth efficiency can be obtained.

Another advantage of the preferred embodiments of the invention is that a faster data transmission using a lesser processing gain is achieved without affecting the performance of transmitters or receivers of the communication system for the same number of bits per symbol compared to existing communication systems.

A further advantage of the preferred embodiments of the invention is that the number of sub-carriers required for representing a symbol in an RNS-based multi-carrier CDMA system can be reduced.

Yet another advantage of the preferred embodiments of the invention is that bandwidth efficiency is enhanced in multicarrier CDMA systems without increasing the number of sub-carriers.

Yet a further advantage of the preferred embodiments of the invention is that, unlike multi-coded communication systems, the number of parallel or serial channels does not change with the number of bits per symbol.

Still a further advantage of the preferred embodiments of the invention is that residues are mutually independent due to carry-free nature and, therefore, residue channels of the communication system can be implemented in parallel.

One more advantage of the preferred embodiments of the invention is that inherent error detection and correction properties of residue numbers can be enhanced further to improve error correction abilities of the communication system.

Another further advantage of the preferred embodiment of the invention is that the number of orthogonal codes required for representing a set of objects in a classification method can be reduced. This is because a group of objects can share the same orthogonal code by assigning distinct data values for each object in the group. The reduction in the number of orthogonal codes is exponentially related to the number of bits used for the representation of objects. Hence, the preferred embodiment of the invention is especially advantageous in communication systems with smaller spreading factor in which the number of available orthogonal codes is limited and is useful in communication systems like home networks.

Referring now to FIG. 3, a general block diagram of a communication system 30 in accordance with a preferred embodiment of the invention is shown. The communication system 30 comprises a transmitting section 31 and a receiving section 32. The transmitting section 31 receives and processes an information bit stream as an input signal. This input signal is then processed for transmission as a spread signal. The spread signal is transmitted to the receiving section 32 via a communication resource 33 such as, for example, a radio frequency (RF) channel. The spread signal is processed by the receiving section 32 to derive the information bit stream.

The transmitting section 31 comprises an outer encoder 34, a binary interleaver 35, a binary-to-residue number system (RNS) converter 36, a residue interleaver 37 and a modulator 38. The information bit stream is encoded by the outer encoder 34 and interleaved by the binary interleaver 35 before conversion to residue values by the binary-to-RNS converter 36. Specifically, the number of bits per symbol, corresponding to M-ary symbols, is selected and converted to the residue values using modulo operations known in the art. Thereafter, the residue values are grouped into frames and interleaved, in frames, by the residue interleaver 37. From the residue interleaver 37, the frames of residue values are provided to the modulator 38 for spread modulating onto the communication resource 33 to thereby provide the spread signal.

The receiving section 32 comprises a demodulator 39, a residue deinterleaver 40, a residue number system (RNS)-to-binary converter 41, a binary deinterleaver 42 and an outer decoder 43. Upon reception at the receiving section 32, the spread signal is demodulated by the demodulator 39 to obtain the residue values. The residue values are then deinterleaved by the residue deinterleaver 40, converted to binary data by the RNS-to-binary converter 41 and provided as input to the binary deinterleaver 42. Output from the binary deinterleaver 42 is decoded by the outer decoder 43 to obtain the information bit stream.

In the communication system 30, the outer encoder 34, the binary interleaver 35, the outer decoder 43 and the binary deinterleaver 42 are considered outside the scope of the invention as described in this specification. Henceforth, these elements are not elaborated upon.

The M-ary symbols are processed into parallel residue channels within the transmitting section 31. To optimize the transmitting section 31, selection of the residue values is important. In addition to satisfying the basic requirements of RNS representation, the dynamic range of a residue set, which is the product of non-redundant residues, should be higher than 2^k, where k is the number of bits per symbol. The difference between the dynamic range and 2^k should be kept to a minimum. Keeping this difference to a minimum helps to maintain the lowest possible spreading factor in the spread signal and reduces search time when an inverse RNS transform and error correction is subsequently performed in the receiving section 32.

FIG. 4 shows a general block diagram illustrating a part of the transmitting section 31 having the RNS converter 36, the residue interleaver 37 and the modulator 38 for parallel modulation of residue channels by a plurality of sub-modulators 45. A fixed set of data symbols, corresponding to an M-ary symbol is converted to residue values by an RNS transform with respect to a fixed moduli set. Residue values

corresponding to an M-ary symbol is termed hereinafter as a residue set. Each residue set represents a symbol and a fixed number of symbols, representing one or more residue sets, are grouped together to form a symbol frame. The residue channels are independently interleaved frame-wise such that each residue channel belonging to the same modulus is not repeated in an interleaved symbol. After interleaving, the binary data of each residue value is modulated and spread by a respective sub-modulator 45. The outputs of the sub-modulators 45 are summed by a combiner 46 and then scrambled with a scrambler 47 to form a spread signal. The scrambler 47 uses a user-specific pseudo random code as the scrambling code. The spread signal is then transmitted out via the communication resource 33.

An example of how residues are interleaved within the residue interleaver 37 is shown in FIGs. 5a and 5b, in which the interleaver depth is nine (9) and is for five residue channels. The residue, x_{mn}, corresponds to the n^{th} residue of the m^{th} symbol. Each column in FIGs. 5a and 5b corresponds to a symbol. FIG. 5a shows positions of the residues before interleaving and FIG. 5b shows positions of the residues after interleaving. From FIGs. 5a and 5b, it can be seen that all columns have unique representations of residue sets. In other words, residues with respect to a modulus are not repeated in the same column. This feature enhances error correction of RNS representation especially when errors occur in bursts.

A general block diagram of a sub-modulator 45 of an n^{th} residue channel of the modulator 38 is shown in FIG. 6. Information bits are spread and modulated within the sub-modulator 45. Each residue channel in the modulation method proposed for the communication system 30 has spread code information and data. In order to extract both the spread code information and the data, a residue channel in the communication system 30 is converted by a binary converting module 55 to binary representation having, for example, k bits. Of these k bits, m least significant bits (LSB) are considered as data and modulated by a modulating module 56 using M-phase shift keying (MPSK)/M-quadrature amplitude modulation (MQAM), where $M = 2^m$. For example, the modulation method is BPSK for $m=1$ and QPSK for $m=2$.

Integers are obtained from the remaining bits *(k-m* bits) for mapping into a set of orthogonal codes based on the Walsh-Hadamard transform at a selected processing gain using a spread code module 57. The MPSK/MQAM modulated symbol for each residue channel is spread with a corresponding spread code and mixed using a mixer module 58 for subsequent transmission. The modules 55,56,57 of the sub-modulator 45 correspond to various stages of modulation and spreading of residues of a residue channel.

Mathematically, the spread signal can be expressed as follows. Assume $\{r_1, r_2, \ldots, r_u\}$ are the residue digits corresponding to moduli $\{m_1, m_2, \ldots, m_u\}$. Since redundant residues are important only for error correction, such redundant residues are not considered for mathematical representation. However, a simple substitution with v (total number of moduli) for u (total number of non-redundant moduli) in the following equations is true for a redundant case. After removing m LSB for MPSK/MQAM modulation, the residue bits are converted to a new set of integers $\{x_1, x_2, \ldots, x_u\}$ such that $max(x_n) = [m_n/M]$, where $[x]$ represents the smallest integer greater than x (a ceiling operation) and $M=2^m$. These integers are then mapped into a set of orthogonal codes $\{C_{1x1}(t), C_{2x2}(t), \ldots C_{uxu}(t)\}$. The total number of such orthogonal codes are nearly $\sum \frac{m_i}{M}$, where $i = 1$ to u and represented as follows:

$$\left\{ \begin{array}{cccc} C_{10}(t) & C_{11}(t) & \ldots\ldots & C_{1\left\lceil \frac{m_1-1}{M} \right\rceil}(t) \\ C_{20}(t) & C_{21}(t) & \ldots\ldots & C_{2\left\lceil \frac{m_2-1}{M} \right\rceil}(t) \\ . & \ldots & \ldots\ldots & . \\ C_{u0}(t) & C_{u1}(t) & \ldots\ldots & C_{u\left\lceil \frac{m_u-1}{M} \right\rceil}(t) \end{array} \right\} \quad (1)$$

These sets of orthogonal codes are used for spreading m LSB for transmission. Each row in the above equation represents the possible set of orthogonal codes corresponding to a particular modulus. The number of rows

represents the number of parallel residue channels required for transmission of an information symbol, which is confined within the limit of the dynamic range. This dynamic range is defined as the product of all non-redundant residues. A spread signal for transmission can be represented as follows:

$$s(t) = \sum_{i=1}^{u} U_{ir_i}(t) \exp(j2\pi f_c t) \quad \text{———} \quad (2)$$

for $0 \leq t < T$, where f_c is the carrier frequency.

$U_{ir_i}(t)$ corresponds to the spread output of modulated data d_m with selected orthogonal code $C_{ix_i}(t)$ of processing gain G for the residue channel i. The following equation represents this operation:

$$U_{ir_i}(t) = \sum_{n=-\infty}^{n=+\infty} \sum_{k=1}^{G} d_m(n) C_{ix_i}(k) p_c(t - kT_c - iT_s) \quad \text{————} \quad (3)$$

where T_c is the chip duration and T_s ($=T_c{*}G$) is the symbol duration. The modulated data d_m is represented as follows:

$$d_m(t) = \sum_{n=-\infty}^{n=+\infty} ej^{(\frac{2\pi(m-1)}{M})} u(t - nT_s), \text{ for MPSK modulation} \quad \text{———} \quad (4)$$

$$d_m(t) = \sum_{n=-\infty}^{n=+\infty} (A_{mc} + jA_{ms}) u(t - nT_s), \text{ for MQAM modulation} \quad \text{———} \quad (5)$$

where m=1,2,...M; A_{mc} and A_{ms} are the information bearing signal amplitudes of the quadrature carriers, and the signal pulse

$$u(t) = \begin{cases} 1(0 \leq t \leq T_s) \\ 0(otherwise) \end{cases}.$$

Similarly, the chip pulse waveform $p_c(t) = \begin{cases} 1(0 \leq t \leq T_c) \\ 0(otherwise) \end{cases}$.

The spread signal transmitted via the communication resource 33 is scattered by many obstacles before reception by the receiving section 32. This creates a multi-path channel for the spread signal. Due to interference in different paths of the spread signal each with a different time delay, the spread signal suffers from frequency

selective multi-path fading and transmission performance is thus significantly degraded. Assuming that the multi-path channel has P (>1) resolvable frequency selective paths, the spread signal received over a multipath channel r(t) can be represented as:

$$r(t)=\sum_{p=0}^{p=-1} r_p(t)=\sum_{p=0}^{p=-1} \alpha_p(t)s(t-\tau_p)+N(t) \quad \text{------} \quad (6)$$

where $N(t)$ represents a stationary zero-mean Gaussian random process with single-sided power spectral density of N_0, and α_p and τ_p are the complex valued channel gain and time delay of p^{th} path $(p=0,1,...P\text{-}1)$, respectively.

A general block diagram of a part of the receiving section 32 having the demodulator 39, the residue deinterleaver 40 and the RNS-to-binary converter 41 is illustrated in FIG. 7. In accordance with RNS arithmetic, the residue operations belonging to different moduli are mutually independent. In line with this, the demodulator 39 is split down to a number of independent sub-demodulators 61 with each dedicated to receive one residue digit associated with each of the residue channels. Hence, the total number of such parallel sub-demodulators 61 is equal to the total number of residue channels. Since the modulator 38 divides each residue channel into spread code information and data, each residue channel of the sub-demodulators 61 is able to retrieve both the spread code information and the data. A general block diagram of a sub-demodulator 61 is shown in FIG. 8. The sub-demodulator 61 includes a spread code selection and ratio statistic measurement module 65 and a MPSK/MQAM demodulation block 66. As discussed earlier, *(k-m)* MSBs of the residue channel corresponds to the spread code used for modulation. Hence by selecting the spread code, the module 65 retrieves (k-m) most significant bits (MSBs) of the residue channel. Once a spread code is determined, it is used for despreading the data as shown in module 67. The data symbols are retrieved by demodulator 66 and considered as m (where m= log2M) least significant bits (LSBs) of the residue channel. The resulting binary sequence from combining MSBs and LSBs are converted back to integers and is considered as an estimated value of residue channel.

Modules in the sub-demodulator 61 have coherent RAKE fingers with an order of diversity that equals the number of paths. FIG. 9 shows a general block diagram of the spread code selection and ratio statistic measurement module 65. The spread code selection and ratio statistic measurement module 65 comprises a multipath despreader 72 followed by a maximum likelihood decision and ratio statistic test module 73. The multipath despreader 71 coherently combines multiple residues of same received signal for all possible orthogonal codes. The channel information corresponding to the multipath channel is estimated using the channel estimation block inside despreader block 71. The estimation can be done either by known data bits (pilot symbols) or/and by known residues (pilot spread codes). Maximum likelihood decision module 73 select the spread code with maximum amplitude. The ratio statistic parameter corresponding to this spread code is determined as discussed in the following paragraph. FIG. 10 shows a general block diagram of a correlator bank 72 of the multipath despreader 71. Assuming perfect synchronization, input to each of the sub-demodulator 61 is descrambled using corresponding scrambling codes and then correlated with a set of orthogonal codes associated with a respective residue channel.

The residues obtained in an RNS-based DS-CDMA system are further supported by a side information called a ratio static test (RST) that drops erroneous residues if transmission of the spread signal uses redundant residue channels. The RST is defined as the ratio of highest to next highest correlator output within the same residue channel and represented as follows:

$$\lambda = \frac{{}^{1}\max_i \left\{ R_{i0}, R_{i1}, \ldots R_{i\left\lceil \frac{mi-1}{M} \right\rceil} \right\}}{{}^{2}\max_i \left\{ R_{i0}, R_{i1}, \ldots R_{i\left\lceil \frac{mi-1}{M} \right\rceil} \right\}} \quad \text{------------} \quad (7)$$

where ${}^{1}max_i\{.\}$ and ${}^{2}max_i\{.\}$ represent the highest and the next highest of the correlator outputs $\{R_{i0}, R_{i1}, \ldots R_{i[mi-1/M]}\}$, where $R_{in} = \sum_{p=1}^{P} \left| R_{in}^{(p)} \right|$ and P is the number of

selected paths in a multipath environment. The RST is based on the assumption that the highest correlator output is significantly higher than the next highest.

Estimated residue values and ratio statistic measures are passed to an error correction/erasure module after a frame-wise de-interleaving. Each symbol is reconstituted with appropriate residue channels. The residue to binary transformation can be done either by a look-up table or by standard methods such as the Chinese remainder theorem or mixed radix conversion. The binary data is again outer de-interleaved and decoded using a suitable error correction code.

Residue numbers corresponding to a symbol can be represented either in parallel or serial. All residue channels corresponding to an interleaved symbol is spread over the same symbol interval for parallel representation. Hence, the total number of parallel channels equals the number of elements in the moduli set. As shown in FIG. 4, a combiner 46 sums these parallel channels before transmission. Adjacent channel interference is minimal due to the orthogonality of individual residue channels. The total number of orthogonal codes required for this method is equal to the sum of all moduli.

Alternatively, the spreading code corresponding to an individual residue is concatenated serially in the symbol interval. In this case, the combiner 46 in FIG.4 is replaced with a parallel to serial conversion module. There is no adjacent channel interference in this case because residue numbers are represented serially. The total number of orthogonal codes required for this method is equal to the largest moduli value.

If the spreading factor is the same whether in parallel or serially, the chip rate for serial concatenation of the spreading code is n_{mod} times higher than the first method, where n_{mod} is the number of moduli. This has a direct implication in computational complexity. On the other hand, if optimal spreading factors are selected based on the sum of moduli for parallel representation and highest modulus

value for serial representation, then the chip rate is nearly the same. Multi-path interference is minimized in the serial concatenation of the spreading code because there is no parallel channel as the orthogonal codes, corresponding to residue values, are serially concatenated. This is more significant especially when the number of symbols is less. Since the symbol spreading duration is nearly same, both parallel representation and serial concatenation show similar performance when the spreading factor is sufficiently high. For all further complexity comparisons, parallel representation is used as a reference.

The modulation method can be used for multi-carrier CDMA systems as well. In multi-carrier transmission, the symbol is spread in the frequency domain and transmitted after inverse Fourier transform. A cyclic prefix is added to reduce the effect of the multi-path interference. At the receiving section 32, the cyclic prefix is removed to detect the orthogonal code on the Fourier transform of the received data. In multi-carrier systems, each sub-carrier represents a chip level information.

For multi-carrier representation of RNS-based CDMA systems, each symbol requires a minimum of Σm_i (sum of all moduli) sub-carriers. By splitting down the residue channels into data and a smaller spread code index, the number of sub-carriers required to represent each orthogonal code can be reduced significantly.

FIGs. 11 and 12 are two general flow charts illustrating the steps in modulating and demodulating by, respectively, the transmitting section 31 and the receiving section 32 of the communication system.

Referring now to FIG. 11, the modulating method 80 starts at step 81 when a binary input signal is received. Thereafter, at step 82, the modulating method 80 continues to step 82 with deriving one or more residue sets from a plurality of bits provided by the binary input signal. Each of the one or more residue sets having one or more residues corresponding to a residue symbol. Also, each of the one or more residue sets has at least one non-redundant residue.

Following step 82, converting each of the one or more residues to binary bits takes place at step 83. Thereafter, at step 84, for each of the one or more residues, one or more least significant bits of the binary bits is modulated to form a modulated symbol. Thereafter, at step 85, an orthogonal code sequence that is associated with remaining bits of the binary bits is selected for each of the one or more residues. In step 86, the modulated symbol is then spread using the orthogonal code sequence to form a residue channel for the each of the one or more residues for transmission.

Demodulating the spread signal received from the transmitting section 31 is generally described in the demodulating method 90 illustrated by the flow chart of FIG. 12. Starting at step 91, the spread signal is received within the communication environment of the communication system 30. Thereafter, at step 92, the spread signal is despread with one or more code sequences associated with each of at least one residue channel to determine a code sequence. The code sequence that is determined is associated with one or more most significant bits and used for transmitting the spread signal for the each of at least one residue channel.

Following step 92, the demodulating method 90 continues to step 93 in which the despread output is demodulated to form an estimated modulated symbol and to derive one or more least significant bits for the each of at least one residue channel. Thereafter, at step 94, the one or more most significant bits and the one or more least significant bits are combined to form a residue associated with the each of the at least one residue channel. A binary output signal is then derived from one or more residue symbols at step 95. Each of the one or more residue symbols is based upon a plurality of residues associated with the at least one residue channel. The plurality of residues corresponds to one or more residue sets.

Table 1 below shows an example of selecting residue numbers for different number of bits per symbol. This table assumes that the total number of residue channels is five in which three moduli are non-redundant *{m_1, m_2 and m_3}* and the

remaining two moduli *{m_4 and m_5}* are used for error detection and correction. While selecting moduli, two constraints are the lowest sum of all possible moduli and the minimum difference between dynamic range and 2^k, where k is the number of bits per symbol. The minimum moduli set possible is *{2, 3, and 5}* and this can represent up to 4 bits per symbol. Hence if the number of bits per symbol is less than 4, the moduli set of *{2, 3, and 5}* needs to be used.

Bits per symbol	Moduli					$\log_2(m_1{*}m_2{*}m_3)$	Sum of moduli (m_i, i =1 to 5)
	M_1	m_2	m_3	m_4	m_5		
4	2	3	5	7	11	4.9069	28
5	3	4	5	7	11	5.9069	30
6	2	5	7	11	13	6.1293	38
7	4	5	7	11	13	7.1293	40
8	5	7	8	9	11	8.1293	40
9	5	9	13	14	17	9.1293	58
10	9	11	13	14	17	10.3298	64
11	11	13	15	17	19	11.0668	75
12	13	17	19	20	21	12.0358	90
13	19	21	22	23	25	13.0997	110
14	25	26	27	29	31	14.0992	138
15	31	33	34	35	37	15.0681	170
16	39	41	43	44	47	16.0692	214
17	50	51	53	59	61	17.0442	274
18	63	64	67	71	73	18.0434	338
19	79	81	82	83	85	19.0012	410
20	101	102	103	107	109	20.0171	522

Table 1: An example for moduli selection for different number of bits per symbol.

Table 2 below shows an example of the modulation method. 16 bits per symbol is selected and the selected moduli set is *{39, 41, 43, 44, 47}*. For QPSK modulation in the modulation method, these moduli are readjusted as below. One extra orthogonal code is required for all moduli to accommodate an all- zero condition in the index. The total number of orthogonal codes can be reduced further by a fine optimization in some cases. For example, for modulus 44, the maximum residue value possible is 43. The binary representation for modulus 44 is 101011 and the decimal value of the preamble portion is 10 for QPSK modulation. Hence the

total number of orthogonal codes required is 11 (to represent 0 to 10), not 12 (to represent 0 to 11) as given in Table 2. However, this kind of optimization is not possible for all moduli values.

Residue values		Proposed Method		
Decimal	Binary	Index to orthogonal code		Data
39	100111	1001	9+1	11
41	101001	1010	10+1	01
43	101011	1010	10+1	11
44	101100	1011	11+1	00
47	101111	1011	11+1	11
Total: 214		Number of orthogonal codes: 56		

Table 2: An example of the modulation method.

Table 3 below shows the minimum processing gain required to represent different number of bits per symbol. As in Table 1, Table 3 also assumes five residue channels in which two are redundant. The calculation is also based on the moduli sets given in Table 1. For M-ary orthogonal based DS-CDMA systems, the minimum spreading gain is two to the power of number of bits per symbol. For RNS-based CDMA systems and for the modulation method, the number of orthogonal codes required for the representation is different from the minimum processing gain. This is because the processing gain of the spread code is a power of two and the minimum number of orthogonal codes required is derived by arithmetic operations on moduli values. For simple RNS-based CDMA systems, the minimum number of orthogonal codes required is the simple addition of all moduli and for the modulation method, the number of orthogonal code is determined after extracting the MPSK/MQAM data from moduli as discussed previously. For Table 3, the modulation method assumes QPSK modulation and hence the total number of orthogonal codes required is approximately ¼ of RNS-based CDMA systems.

Bits/ Symbol	M-ary	RNS based CDMA			Proposed Method		
		Σm_i	Parallel	Serial	$\Sigma[m_i/M]$	Parallel	Serial
4	16	28	32	16*5	9	16	4*5
5	32	30	32	16*5	9	16	4*5
6	64	38	64	16*5	12	16	4*5
7	125	40	64	16*5	12	16	4*5
8	256	40	64	16*5	12	16	4*5
9	512	58	64	32*5	18	32	8*5
10	1024	64	64	32*5	19	32	8*5
11	2048	75	128	32*5	21	32	8*5
12	4096	90	128	32*5	25	32	8*5
13	8192	110	128	32*5	30	32	8*5
14	16834	138	256	32*5	37	64	8*5
15	32768	170	256	64*5	45	64	16*5
16	65536	214	256	64*5	55	64	16*5
17	131072	274	512	64*5	71	128	16*5
18	262144	338	512	128*5	86	128	32*5
19	524288	410	512	128*5	105	128	32*5
20	1048576	522	1024	128*5	133	256	32*5

Table 3: Relationship between processing gain and number of bits per symbol for different modulation methods for the moduli set given in Table 1.

Table 3 also shows the processing gain required if all residue digits are represented by serial concatenation of spread codes. In this case, the spreading factor for each residue value should be higher than the maximum moduli value. For the modulation method, the maximum spreading factor is determined after separating data values from moduli. Since the spread codes are serially concatenated, the processing gain for each symbol is n_{mod} multiplied by the spreading factor, where n_{mod} is the number of moduli.

It is obvious from the table that the spreading factor of M-ary orthogonal-based DS-CDMA systems increases exponentially with the number of bits per symbol. However, if the number of bits per symbol is less than five, then a lesser number of orthogonal codes is required in M-ary orthogonal based DS-CDMA systems than alternative methods. Between parallel and serial concatenation of spread codes, the processing gain is less for parallel channels. However, each residue channel has a higher spreading gain. This difference decreases when the number of symbol per bits increases. In some cases (for example, when number of bits per

symbol is 17 or 20), the processing gain of serially concatenated spread codes is less than parallel spread code representation.

For further complexity analysis, the Yang and Hanzo modulation method is compared against the modulation method with parallel channels applied in the communication system 30. A graphical representation of changes in the processing gain with number of bits per symbol for M-ary orthogonal based DS-CDMA systems, the Yang and Hanzo modulation method and the proposed modulation method is given in FIG. 13. Only parallel representation of residue channels is given. The results corresponding to serially concatenated spread code also shows a similar trend.

It can be seen that for M-ary orthogonal based DS-CDMA systems, the processing gain changes exponentially with the number of bits per symbol while variation in the processing gain for the other modulation methods is more or less linear. Also, the required number of orthogonal codes is the least for the proposed modulation method. Data modulation within the sub-modulator 45 determines the reduction of processing gain for the proposed modulation method. For example, for QPSK modulation, the processing gain of the proposed modulation method is reduced by a factor of four.

These changes in spreading factor affect the complexity of the receiver. The computational saving for an M-ary orthogonal based DS-CDMA system using the proposed modulation method is significant. Table 4 below compares the computational complexities of the receivers of the M-ary orthogonal based DS-CDMA system, the Yang and Hanzo modulation method and the proposed modulation method. Table 4 assumes that each symbol consists of k bits, and v residues are used to represent each symbol in an RNS representation. The residues are $\{m_1, m_2, m_3, \ldots, m_v\}$. For the proposed modulation method, MPSK/MQAM modulation is used for data where $M = 2^m$. The complexity of the RNS encoder and the RNS decoder are not considered for this analysis. However, forward and reverse

conversion using RNS is minimal when considering the total number of complex multiplication required per symbol and is well documented.

	M-ary CDMA	Yang and Hanzo Method	Proposed Method (parallel representation)
Number of Spread codes	2^k	Σm_i, where i = 1 to v	$\Sigma[m_i/M]$, where i = 1 to v
Minimum Processing gain	2^k	2^x, where $2^x > \Sigma m_i > 2^{x-1}$	2^y, where $2^y > \Sigma\, [m_i/M] > 2^{y-1}$
Demodulation	Coherent/ Non-coherent	Coherent/ Non-coherent	Coherent + MPSK demodulation
Data bits/symbol	Nil	Nil	$m = \log_2(M)$
No. of parallel channels	1	v	v
Error Correction	External	Can add redundant residues	Can add redundant residues
Correlator banks/symbol	2^k	Σm_i	$\Sigma\, [m_i/M]$
Min. number of complex multiplication /symbol	$(2^k) * (2^k)$	$\Sigma\, (m_i) * (2^x)$	$(\Sigma\, [m_i/M]) * (2^y)$

Table 4: Comparison of computational complexities in the receiver design of an M-ary orthogonal based DS-CDMA system, the Yang and Hanzo modulation method and the proposed modulation method.

For example, Table 5 below compares the computational complexity for a typical case given in Table 1. For an RNS-based CDMA system having 16 bits per symbol, the moduli set is *{39, 41, 43, 44, 47}*. QPSK data modulation is used in the transmitter.

	M-ary orthogonal based DS-CDMA system	Yang and Hanzo modulation method	Proposed modulation method (parallel)
Spread codes	65536	214	55
Min. processing gain	65536	256	64
Data bits/Symbol	Nil	Nil	2
Parallel Channels	1	5	5
Error correction	Nil	one residue channel can be corrected	one residue channel can be corrected
Correlator banks symbol	65536	214	55
Min. no. of complex multiplication /symbol	65536*65536	256*214 (=54784)	64*55 (=3520)

Table 5: Comparison of computational complexities of a typical system using 16 bits per symbol and having the moduli set *{39, 41, 43, 44, 47}*

FIG. 14 is a comparative graph of computational complexities for the communication system 30 with prior art systems. The number of floating point operations required per symbol is selected as a measure of computational complexity. It is clearly evident that the M-ary orthogonal based DS-CDMA system has exponential complexity with number of bits per symbol. The proposed modulation method has the least computational complexity than all other modulation methods discussed. It is partly because of the lesser number of spread codes after data modulation. FIG. 14 assumes QPSK modulation for the proposed modulation method. Any change in this modulation reflects in complexity also. The higher the number of data bits modulated, the lesser the number of spread codes and hence the lesser computational complexity. But the detection accuracy is affected when the number of data bits (m) is more. The relation between computational complexity and spread code is more obvious when FIG. 13 and FIG. 14 are compared.

Computer simulations evaluate the bit-error-rate (BER) performance of the proposed modulation method. Table 6 below shows simulation parameters.

Total bandwidth		5MHz		
Chip rate		4.096 Mcps		
Processing gain	Method 1	128	64	32
	Method 2	32*5	16*5	8*5
Symbol rate (Ksps)	Method 1	32	64	128
	Method 2	25.6	51.2	102.4
Bits per symbol		18	16	12
Channel bit rate (Kbps)	Method 1	576	1024	1536
	Method 2	460.8	819.2	1228.8
No. of residue channels		5 (3 non-redundant, 2 for error correction)		
Modulation		QPSK + M-ary orthogonal modulation		
Channel model		L path Rayleigh channel with slow fading		
Spreading code	Short code	Orthogonal Walsh sequence		
	Long code	Random sequence		
RAKE diversity		1-20 symbol time window		
Symbol interleaving		Frame wise (16 slot/frame, 18 symbols/slot)		
Channel coding	Inner	RNS coding		
	Outer	Nil		
Power control		Nil		

Table 6: Simulation parameters for the proposed modulation method. Method 1 uses parallel transmission residue channels and Method 2 uses serial concatenation of residue codes.

The modulation method assumes constant chip rate and is fixed at 4.096 Mcps. Since the modulation method uses orthogonal modulation and constant chip rate, the spreading factor is the most important design parameter that determines symbol rate, moduli values and, thereby, channel bit rate. The computer simulations are carried out for different spreading factors such as 128, 64 and 32. The proposed

modulation method, with parallel and serial representations, is compared for all these spreading factors.

The proposed modulation method can bring down the spreading factor to ¼ times if the data is QPSK modulated. The simulated communication system uses five residue channels in which three are non-redundant. Also, orthogonal Walsh sequence is used as short code and pseudo-random codes are used as long codes for spreading. Rayleigh channel with slow fading is used as a channel model. No other channel coding methods are employed except RNS coding of channel bits. The simulated communication system assumes accurate synchronization and accurate estimation of multipath channel conditions. Power control methods are not considered. The following section summarizes the simulation results.

FIGs. 15a and 15b compare performance of the communication system 30 with prior art systems in a Rayleigh fading channel. The performance is compared for 16 bits per symbol and a corresponding moduli set is *{39, 41, 43, 44, 47}*. Here, QPSK modulation for data is assumed. Compared with conventional RNS-based CDMA systems, the modulation method is capable of bringing down the processing gain by about ¼ of the original processing gain.

In particular, FIG. 15a gives the performance characteristics for the communication system 30 with parallel representation of residue channels. By applying the modulation method, the minimum processing gain can be reduced to 64 for the communication system 30. The system characteristics are plotted for single path, two paths and three paths. The BER performance improves as the number of paths increases due to the diversity gain in the combining.

FIG. 15b shows the performance corresponding to the serial concatenation of residue codes. The minimum number of orthogonal codes required is the highest moduli value and the corresponding spreading factor is the nearest power of two. The individual spreading factor for each residue value is 16 in this case and the total

number of chips per symbol is 16*5, where 5 is the number of residue channels. The performance is plotted for a multi-path environment. Since the spreading per symbol is nearly same in both cases, the performance is more or less comparable.

On the average, the performance of the communication system 30 is better than the prior art systems. For lower Eb/No regions, multi-coded CDMA systems gives a better performance. This is largely because of the definiteness in the spread code selection of the proposed modulation method whereas the spread code selection in the alternative modulation methods is preceded by a decision making process, which may not be accurate for low Eb/No. If the Eb/No is sufficiently high, the performances of the alternative modulation methods surpasses that of the multi-coded CDMA systems.

The communication system 30 outperforms the RNS-based CDMA system proposed by Yang and Hanzo in all the cases. This is likely because of the hybrid nature of the communication system 30 in which the modulation system is implemented.

The performance of the communication system 30 with reduced processing gain compared to that with normal processing gain is to be noted. As shown, the reduced processing gain does not affect the performance of the communication system. This clearly provides an indication of a high data transfer rate using the communication system 30 without affecting the performance. In FIG. 16, it is seen that if the processing gain is sufficiently high, the communication system 30 with reduced processing gain sometimes outperforms another communication system with normal processing gain.

In order to complete the comparison, the communication system 30 with reduced processing gain is compared against the alternative modulation methods having lower processing gains. The performance results are given in FIG. 17. The moduli and the number of bits in both the communication system 30 and other

communication systems using the alternative modulation methods are different. In FIG. 17, the processing gain is 64 and the number of bits per symbol is 16 for the communication system 30 and 9 for the Yang and Hanzo prior art systems. In the multi-coded CDMA system, the number of bits per symbol is kept the same as the communication system 30.

FIG. 17 clearly shows that the performance of the communication system 30 is far superior to the prior art systems. Hence, from computer simulations, it can be concluded that the communication system 30 in which the modulation method is applied can give better throughput with better BER performance.

FIG. 18 is a general block diagram illustrating a part of the transmitting section 31 in accordance with an alternate embodiment of the invention. It is to be noted that the residue interleaver 37 is the same for both embodiments and has been described earlier. However, the alternate embodiment has a modulator 101 for multicarrier modulation. The modulator 101 has other elements in addition to that of the modulator 38.

In the alternate embodiment, residues are provided as binary input to the residue interleaver 37 and then to the modulator 101. Each of the residues is transmitted through a respective sub-modulator 45. Outputs from the sub-modulators 45 are combined by the combiner 46 and then scrambled by the scrambler 47 using a scrambling code. The scrambling code is usually a pseudo-random code that is user specific. Scrambled output from the scrambler 47 is converted into parallel by a serial-to-parallel converter 102 and provided to an inverse fast Fourier transform (IFFT) module 104. Optionally, a sub-carrier interleaver 103 can be inserted before the IFFT module 104 to reduce the effect of severe frequency-selective fading in the channel. A guard interval is inserted by a timer 105 between symbols to avoid inter-symbol interference due to multipath fading. The signal thus formed is then transmitted as a spread signal after radio frequency up-conversion.

As discussed in the preferred embodiment, parallel and serial representation of residues can be used. In parallel representation of residues, the number of sub-carriers used for each individual residue will be higher than the sum of all moduli and all residues are transmitted in parallel using orthogonal spread code mapping as discussed earlier. In serial representation, the number of sub-carriers used for individual residues is higher than the largest moduli value. Unlike the preferred embodiment where all sub-carriers are used for all residues, each residue is transmitted through to a distinct set of sub-carriers in the alternate embodiment. FIG. 18 corresponds to parallel transmission of residues. For serial transmission, the combiner 46 is interchanged with a parallel to serial converter (not shown). Hence, for serial transmission it is possible to directly provide output from the sub-modulator 45 to the IFFT module 104 after scrambling each sub-carrier since the scrambler 47 and the serial-to-parallel converter 102 follow the combiner 46.

Demodulation of a spread signal in the alternate embodiment for a multicarrier CDMA system is different from that of the preferred embodiment. Such demodulation requires the receiving section 32 to be modified as shown in the general block diagram of FIG. 19. In the receiving section 32 of the alternate embodiment, a demodulator 110 has different elements compared to that of the demodulator 39. However, the residue deinterleaver 40, the RNS-to-binary converter 41, the binary deinterleaver 42 and the outer decoder 43 remain the same as in the preferred embodiment.

In the alternate embodiment, the spread signal is down-converted from radio frequency and then accurately synchronized with symbol interval to provide an output signal. The guard interval is removed from each symbol of the output signal by a receiver timer 111 and the output signal is then provided to a fast Fourier transform (FFT) module 112 to generate sub-carrier signals. Thereafter, a parallel-to-serial converter 114 converts the sub-carrier signals for the sub-demodulators 115. Optionally, a sub-carrier deinterleaver 113 can be inserted after the FFT module 112 if the spread signal has sub-carriers that are interleaved. The sub-carrier allocation in

each of the sub-demodulators 115 corresponds to the sub-carrier allocation in the sub-modulators 45 of the modulator 101. Residue deinterleaving and RNS-to-binary conversion is applied to the output from the sub-demodulators 115.

The structure of each of the sub-demodulators 115 of the alternate embodiment is different from the sub-demodulators 61 of the preferred embodiment. After removal of the guard interval, which eliminates inter-symbol interference, the sub-demodulators 115 in the alternate embodiment does not require multipath combining. Accordingly, a general block diagram for the sub-demodulators 115 is shown in FIG 20. A pilot symbol assisted channel estimation method is used to estimate channel parameters in a channel estimation block 120 and an equalizer 121 adjusts channel coefficients based on adaptive equalization algorithms for compensating possible channel distortions. For a single path system, this is similar to combining the general block diagrams of FIGs. 8 and 9 of the preferred embodiment. A correlator bank 122 shown in FIG 8A is similar to the correlator bank 72 shown in FIG. 10. The path delay parameter τ_n in FIG. 10 is assumed to be zero for a single path system. Other elements in FIG. 20 corresponds to those of the preferred embodiment as illustrated in FIGs. 8 and 9.

The relationship between processing gain and number of bits per symbol for different modulation methods given in Table 3 are true for RNS-based multicarrier CDMA systems as well. Here the processing gain corresponds to the number of sub-carriers required for transmission. For effective implementation of FFT, the number of sub-carriers is selected as the nearest powers of two. This aspect needs to be considered when deciding the number of moduli sets in residue number systems, especially for serial representation.

The communication system 30 provides an alternative for high-speed data transmission, such as, high speed wireless local area networks (LANs). Here, a fixed number of data symbols are converted to RNS representation and then each residue is transmitted through parallel/serial channels after appropriate modulation. Hence,

more number of bits is used for data modulation, which can further increase the data rate. The error correction abilities of RNS systems are exploited for the possible error correction. Since this increases the data rate significantly, the communication system 30 can be considered as a candidate for the next generation of mobile communication systems and high-speed wireless local area networking (WLAN) systems.

In the foregoing description, communication system 30, a modulation method 80 and a demodulation method 90 based on the residue number system (RNS) for the communication system 30 are described. Although preferred embodiments are described, it shall be apparent to one skilled in the art in view of these preferred embodiments that numerous changes and/or modifications can be made without departing from the scope and spirit of the invention.

Claims:

1. A method for modulating a binary input signal to form a spread signal for transmission, said method comprising the steps of:

   deriving one or more residue sets from a plurality of bits provided by said binary input signal, each of said residue sets having one or more residues, corresponding to a residue symbol, and having at least one non-redundant residue;

   converting each of said residues to binary bits;

   modulating one or more least significant bits of said binary bits to form a modulated symbol for each of said residues;

   selecting an orthogonal code sequence associated with remaining bits of said binary bits for each of said residues;

   and

   spreading said modulated symbol for each of said residues using said selected orthogonal code sequence to form a residue channel for each of said residues for transmission.

2. The method as claimed in Claim 1, wherein said converting step comprises the step of grouping said residue sets to form a symbol frame.

3. The method as claimed in Claim 2, wherein said converting step further comprises the step of interleaving said residues from said symbol frame to form an interleaved residue frame.

4. The method as claimed in Claim 3, wherein said interleaving step comprises the step of arranging said residues based upon an interleaving depth of said interleaved residue frame and the number of said residue channel.

5. The method as claimed in Claim 4, wherein said arranging step comprises the step of setting said interleaving depth based upon the number of said residue sets.

6. The method as claimed in Claim 1, and further comprising the step of combining output from each residue channel to form said spread signal.

7. The method as claimed in Claim 6, wherein said combining step is carried out in parallel.

8. The method as claimed in Claim 6, wherein said combining step comprises serially concatenating said output.

9. The method as claimed in Claim 6, and further comprising the step of scrambling said spread signal using a predetermined scrambling code.

10. The method as claimed in Claim 6, and further comprising the steps of:
converting said spread signal to parallel outputs;
and
inverse Fast Fourier transforming said parallel outputs to form transformed outputs.

11. The method as claimed in Claim 10, wherein said converting step comprises the step of interleaving said spread signal.

12. The method as claimed in Claim 10, and further comprising the step of scrambling said spread signal using a predetermined scrambling code prior to said converting step.

13. The method as claimed in Claim 10, and further comprising the step of inserting a guard interval between said transformed outputs prior to transmission.

14. A method for demodulating a spread signal received within a communication environment, said method comprising the steps of:

despreading said spread signal with one or more code sequences associated with each of at least one residue channel to determine a code sequence, said code sequence being associated with one or more most significant bits and used for transmitting said spread signal for each residue channel;

demodulating despread output corresponding to the determined code sequence to form an estimated modulated symbol and subsequently derive one or more least significant bits for each residue channel;

combining said one or more most significant bits and said one or more least significant bits to form a residue associated with each residue channel;

and

deriving a binary output signal from one or more residue symbols, each of said one or more residue symbols being based upon a plurality of residues associated with said at least one residue channel, said plurality of residues corresponding to one or more residue sets.

15. The method as claimed in Claim 14, wherein said despreading step comprises the step of applying a ratio static test on each of said despread output to obtain test statistics for each of said one or more residues.

16. The method as claimed in Claim 15, wherein said deriving step comprises the step of choosing non-redundant residues for each of said one or more residue sets based on corresponding said test statistics for each of said one or more residues.

17. The method as claimed in Claim 14, wherein said despreading step comprises the step of estimating channel status information associated with each residue channel.

18. The method as claimed in Claim 17, wherein said demodulating step comprises the step of forming said estimated modulated symbol using said despread output of selected spread code and estimated channel status information associated with each residue channel.

19. The method as claimed in Claim 14, and further comprising the step of forming an interleaved residue frame from said plurality of residues.

20. The method as claimed in Claim 19, wherein said forming step comprises the step of deinterleaving said interleaved residue frame to form a symbol frame, said symbol frame having one or more residue sets based upon said plurality of residues, each of said residue sets representing a symbol.

21. The method as claimed in Claim 20, wherein said deinterleaving step comprises the step of setting an interleaved depth for said interleaved residue frame based upon the number of said residue sets.

22. The method as claimed in Claim 14, and further comprising the step of descrambling said spread signal using a predetermined scrambling code.

23. The method as claimed in Claim 14, and further comprising the steps of:

converting said spread signal to parallel outputs;

and

Fast Fourier transforming said parallel outputs to form transformed outputs.

24. The method as claimed in Claim 23, and further comprising the step of descrambling said spread signal using a predetermined scrambling code prior to said converting step.

25. The method as claimed in Claim 24, wherein said converting step comprises the step of deinterleaving said spread signal.

26. A communication system having a transmitting section for modulating a binary input signal to form a spread signal for transmission, said communication system comprising:

means for deriving one or more residue sets from a plurality of bits provided by said binary input signal, each of said residue sets having one or more residues, corresponding to a residue symbol, and having at least one non-redundant residue;

means for converting each of said residues to binary bits;

means for modulating one or more least significant bits of said binary bits to form a modulated symbol for each of said residues;

means for selecting an orthogonal code sequence associated with remaining bits of said binary bits for each of said residues;

and

means for spreading said modulated symbol for each of said residues using said selected orthogonal code sequence to form a residue channel for each of said residues for transmission.

27. The communication system as claimed in Claim 26, wherein said converting means comprises means for grouping said residue sets to form a symbol frame.

28. The communication system as claimed in Claim 27, wherein said converting means further comprises means for interleaving said residues from said symbol frame to form an interleaved residue frame.

29. The communication system as claimed in Claim 28, wherein said interleaving means comprises means for arranging said residues based upon an interleaving depth of said interleaved residue frame and the number of said residue channel.

30. The communication system as claimed in Claim 29, wherein said arranging means comprises means for setting said interleaving depth based upon the number of said residue sets.

31. The communication system as claimed in Claim 26, and further comprising means for combining output from each residue channel to form said spread signal.

32. The communication system as claimed in Claim 31, wherein said combining means comprises means for carrying out said combining in parallel.

33. The communication system as claimed in Claim 31, wherein said combining means comprises means for serially concatenating said output.

34. The communication system as claimed in Claim 31, and further comprising means for scrambling said spread signal using a predetermined scrambling code.

35. The communication system as claimed in Claim 31, and further comprising:

means for converting said spread signal to parallel outputs; and

means for inverse Fast Fourier transforming said parallel outputs to form transformed outputs.

36. The communication system as claimed in Claim 35, wherein said converting means comprises means for interleaving said spread signal.

37. The communication system as claimed in Claim 35, and further comprising means for scrambling said spread signal using a predetermined scrambling code prior to said converting.

38. The communication system as claimed in Claim 35, and further comprising means for inserting a guard interval between said transformed outputs prior to transmission.

39. A communication system having a receiving section for demodulating a spread signal received within a communication environment, said communication system comprising:

means for despreading said spread signal with one or more code sequences associated with each of at least one residue channel to determine a code sequence, said code sequence being associated with one or more most significant bits and used for transmitting said spread signal for said each of at least one residue channel;

means for demodulating despread output corresponding to the determined spread code to form an estimated modulated symbol and subsequently derive one or more least significant bits for said each of at least one residue channel;

means for combining said one or more most significant bits and said one or more least significant bits to form a residue associated with each residue channel;

and

means for deriving a binary output signal from one or more residue symbols, each of said one or more residue symbols being based upon a plurality of residues associated with said at least one residue channel, said plurality of residues corresponding to one or more residue sets.

40. The communication system as claimed in Claim 39, wherein said despreading means comprises means for applying a ratio static test on each of said despread output to obtain test statistics for each of said one or more residues.

41. The communication system as claimed in Claim 40, wherein said deriving means comprises means for choosing non-redundant residues for each of said one or more residue sets based on corresponding said test statistics for each of said one or more residues.

42. The communication system as claimed in Claim 39, wherein said despreading means comprises means for estimating channel status information associated with each residue channel.

43. The communication system as claimed in Claim 42, wherein said demodulating means comprises means for forming said estimated modulated symbol using said despread output of selected spread code and estimated channel status information associated with said each of at least one residue channel.

44. The communication system as claimed in Claim 39, and further comprising means for forming an interleaved residue frame from said plurality of residues.

45. The communication system as claimed in Claim 44, wherein said forming means comprises means for deinterleaving said interleaved residue frame to form a symbol frame, said symbol frame having one or more residue sets based upon said plurality of residues, each of said residue sets representing a symbol.

46. The communication system as claimed in Claim 45, wherein said deinterleaving means further comprises means for setting an interleaved depth for said interleaved residue frame based upon the number of said residue sets.

47. The communication system as claimed in Claim 39, and further comprising means for descrambling said spread signal using a predetermined scrambling code.

48. The communication system as claimed in Claim 39, and further comprising:

means for converting said spread signal to parallel outputs; and

means for Fast Fourier transforming said parallel outputs to form transformed outputs.

49. The communication system as claimed in Claim 48, and further comprising means for descrambling said spread signal using a predetermined scrambling code prior to said converting.

50. The communication system as claimed in Claim 49, wherein said converting means comprises means for deinterleaving said spread signal.

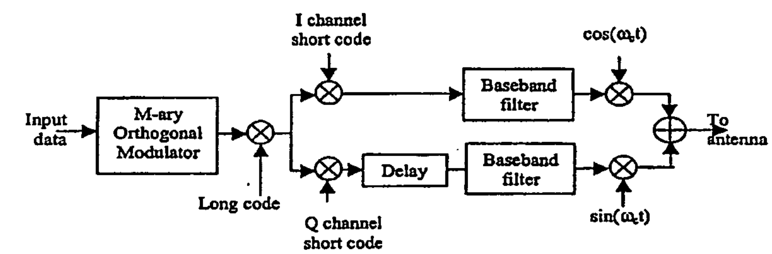


FIG. 1 [Prior Art]

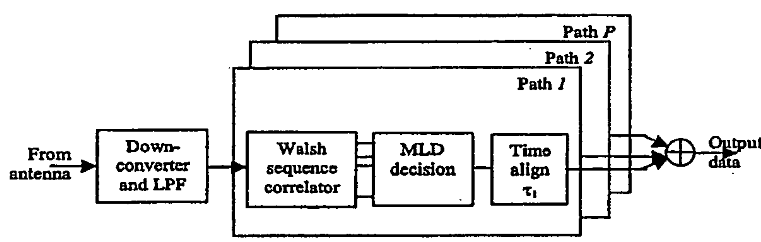


FIG. 2 [Prior Art]

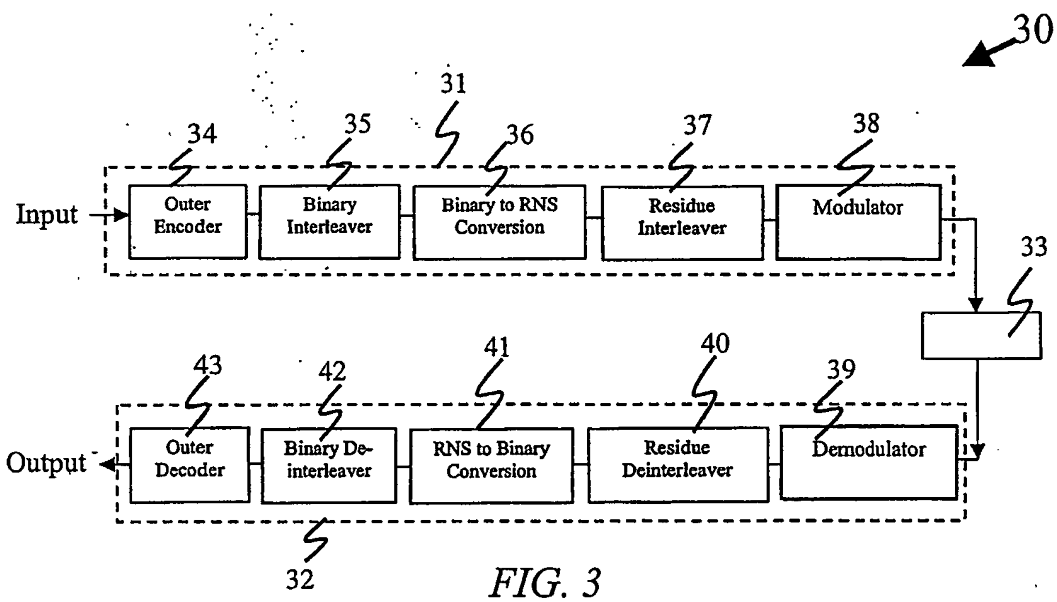

30
31
34
35
36
37
38
Input
Outer Encoder
Binary Interleaver
Binary to RNS Conversion
Residue Interleaver
Modulator
33
43
42
41
40
39
Output
Outer Decoder
Binary De-interleaver
RNS to Binary Conversion
Residue Deinterleaver
Demodulator
32

FIG. 3

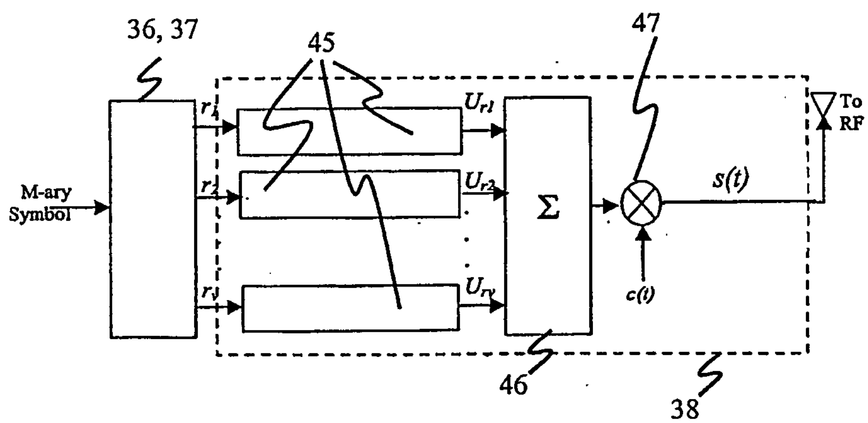

36, 37
45
47
M-ary Symbol
r_1
r_2
r_v
U_{r1}
U_{r2}
U_{rv}
Σ
s(t)
c(t)
To RF
46
38

FIG. 4

50

51

x_{11}	x_{21}	x_{31}	x_{41}	x_{51}	x_{61}	x_{71}	x_{81}	x_{91}
x_{12}	x_{22}	x_{32}	x_{42}	x_{52}	x_{62}	x_{72}	x_{82}	x_{92}
x_{13}	x_{23}	x_{33}	x_{43}	x_{53}	x_{63}	x_{73}	x_{83}	x_{93}
x_{14}	x_{24}	x_{34}	x_{44}	x_{54}	x_{64}	x_{74}	x_{84}	x_{94}
x_{15}	x_{25}	x_{35}	x_{45}	x_{55}	x_{65}	x_{75}	x_{85}	x_{95}

FIG. 5 (a)

x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	x_{21}	x_{22}	x_{23}	x_{24}
x_{25}	x_{31}	x_{32}	x_{33}	x_{34}	x_{35}	x_{41}	x_{42}	x_{43}
x_{44}	x_{45}	x_{51}	x_{52}	x_{53}	x_{54}	x_{55}	x_{61}	x_{62}
x_{63}	x_{64}	x_{65}	x_{71}	x_{72}	x_{73}	x_{74}	x_{75}	x_{81}
x_{82}	x_{83}	x_{84}	x_{85}	x_{91}	x_{92}	x_{93}	x_{94}	x_{95}

FIG. 5 (b)

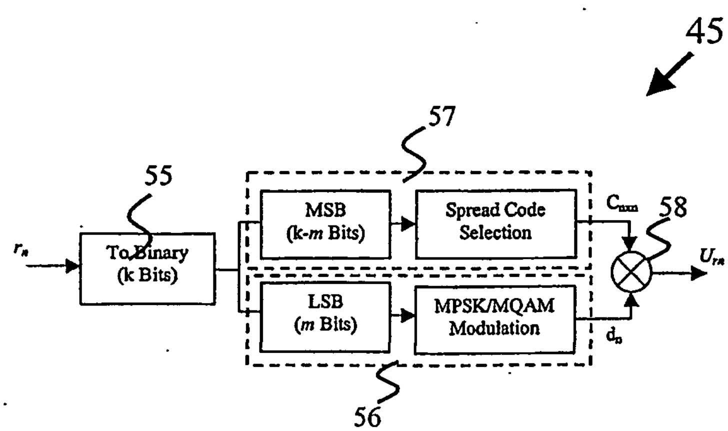


FIG. 6

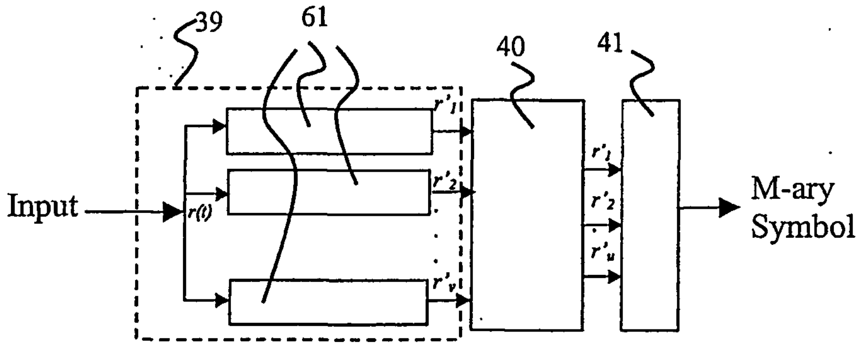

39
61
40
41
Input
r(t)
M-ary Symbol

FIG. 7

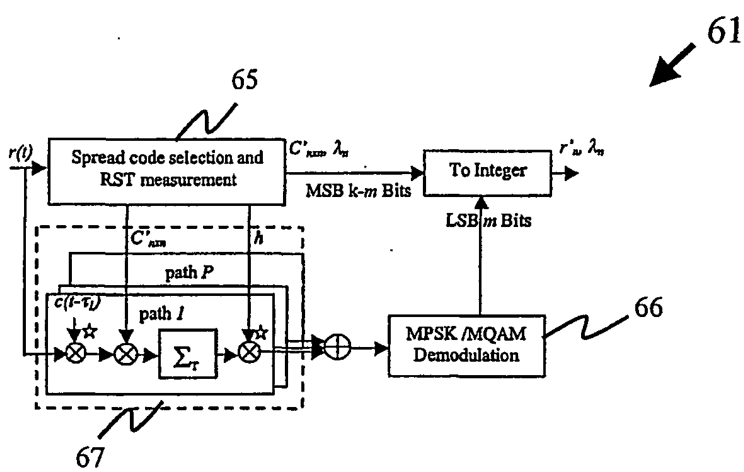
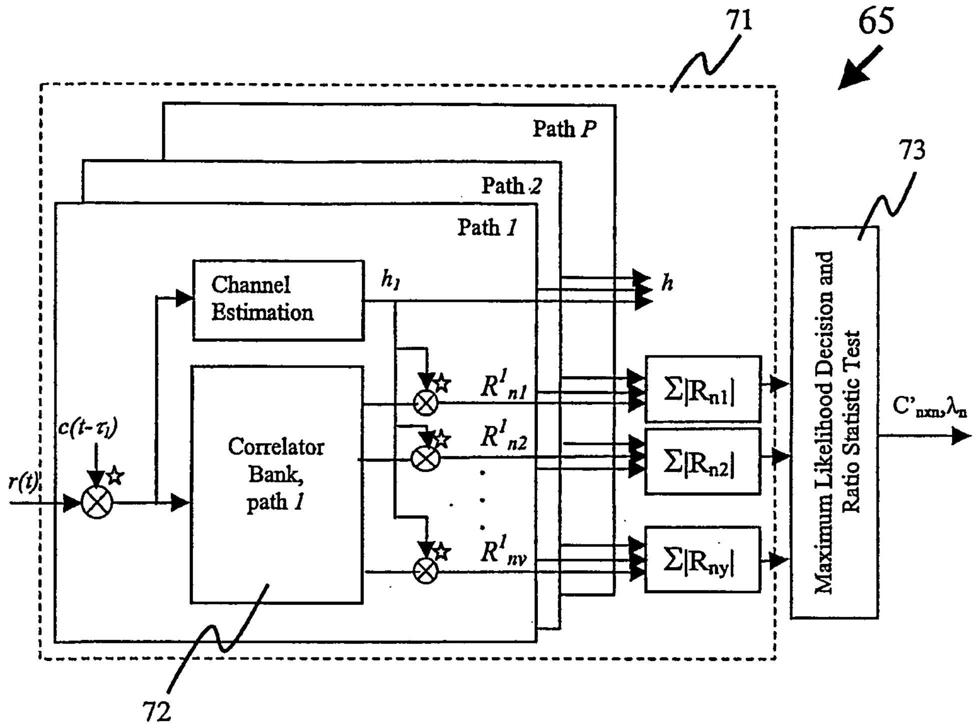
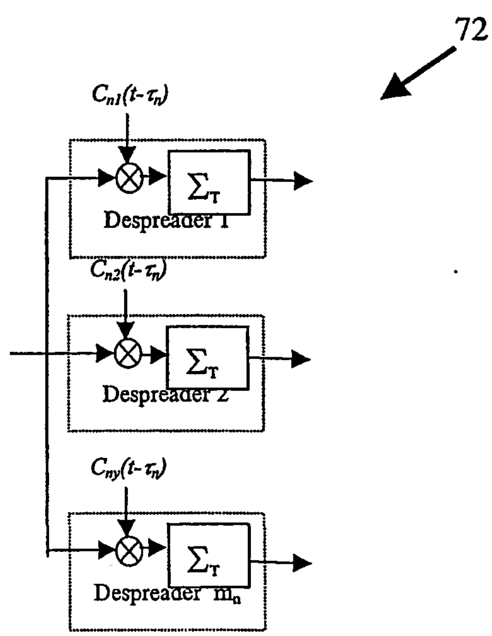

61
65
r(t)
Spread code selection and RST measurement
MSB k-m Bits
To Integer
LSB m Bits
path P
path 1
MPSK /MQAM Demodulation
66
67

FIG. 8



71
65
Path P
Path 2
Path 1
73
Channel Estimation
h1
h
c(t-τ1)
r(t)
Correlator Bank, path 1
R1n1
R1n2
R1ny
Σ|Rn1|
Σ|Rn2|
Σ|Rny|
Maximum Likelihood Decision and Ratio Statistic Test
C'nxm,λn
72

FIG. 9



72
Cn1(t-τn)
ΣT
Despreader 1
Cn2(t-τn)
ΣT
Despreader 2
Cny(t-τn)
ΣT
Despreader mn

FIG. 10

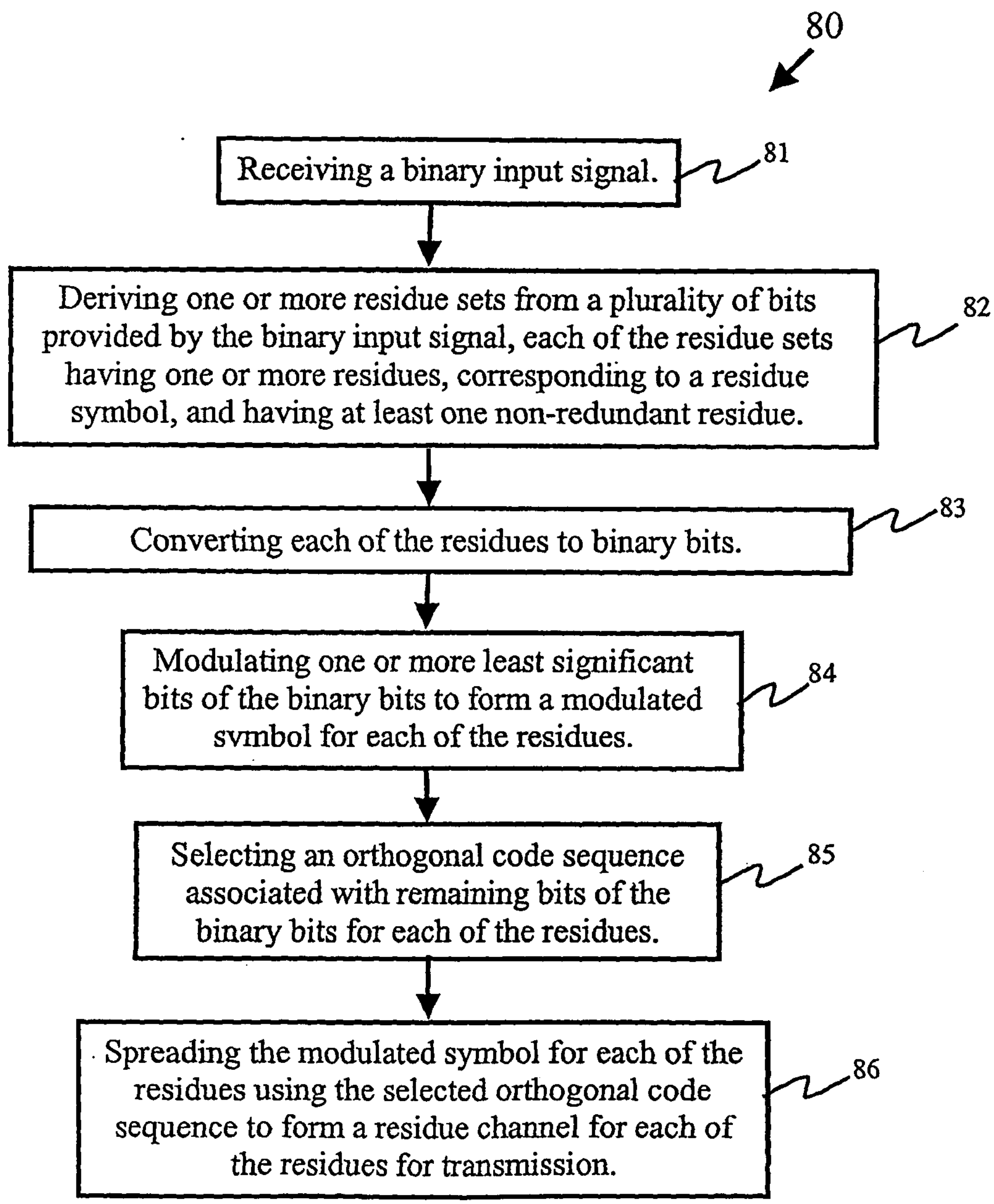

80
Receiving a binary input signal.
81
Deriving one or more residue sets from a plurality of bits provided by the binary input signal, each of the residue sets having one or more residues, corresponding to a residue symbol, and having at least one non-redundant residue.
82
Converting each of the residues to binary bits.
83
Modulating one or more least significant bits of the binary bits to form a modulated svmbol for each of the residues.
84
Selecting an orthogonal code sequence associated with remaining bits of the binary bits for each of the residues.
85
Spreading the modulated symbol for each of the residues using the selected orthogonal code sequence to form a residue channel for each of the residues for transmission.
86

FIG. 11

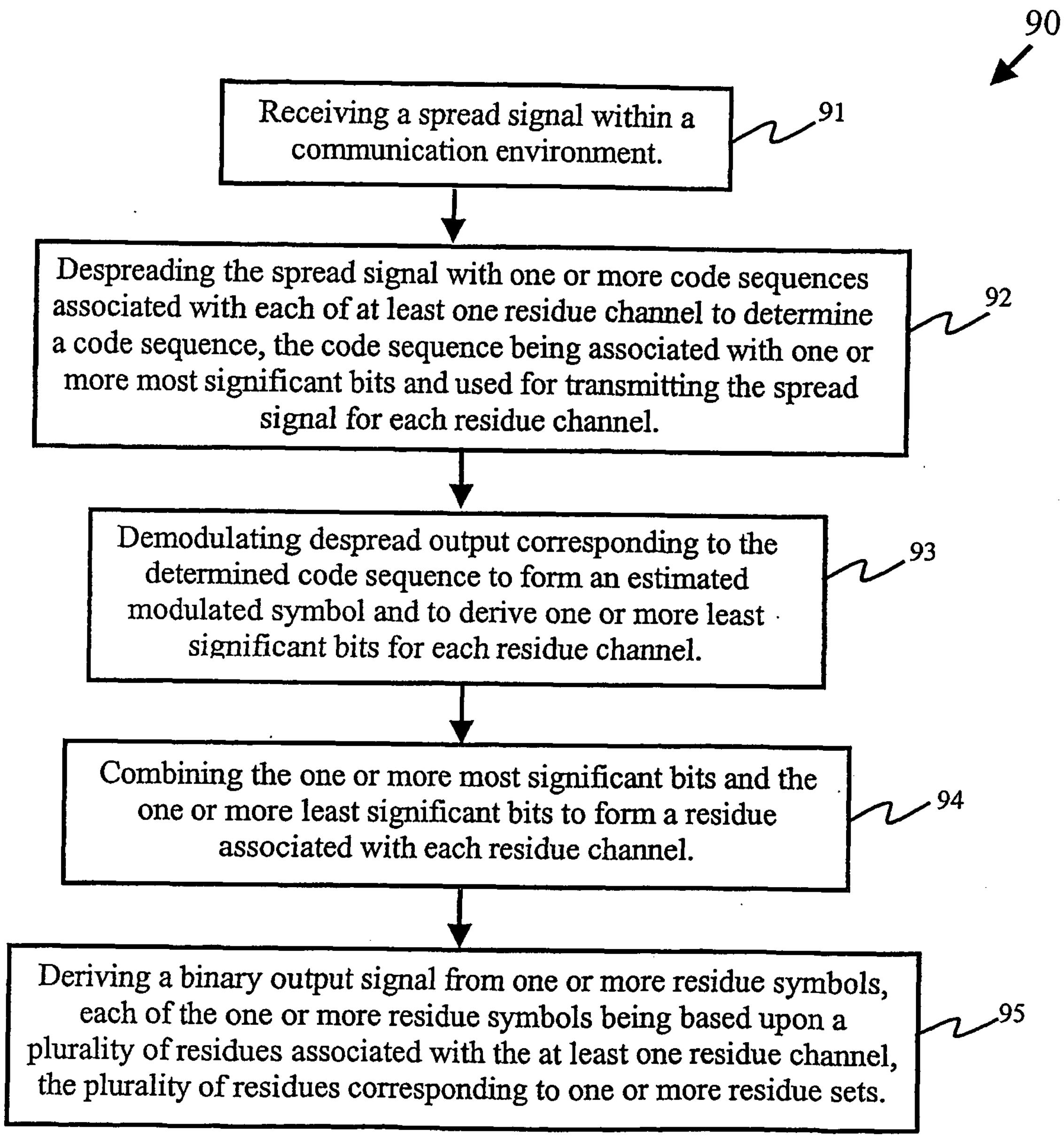

90
Receiving a spread signal within a communication environment.
91
Despreading the spread signal with one or more code sequences associated with each of at least one residue channel to determine a code sequence, the code sequence being associated with one or more most significant bits and used for transmitting the spread signal for each residue channel.
92
Demodulating despread output corresponding to the determined code sequence to form an estimated modulated symbol and to derive one or more least significant bits for each residue channel.
93
Combining the one or more most significant bits and the one or more least significant bits to form a residue associated with each residue channel.
94
Deriving a binary output signal from one or more residue symbols, each of the one or more residue symbols being based upon a plurality of residues associated with the at least one residue channel, the plurality of residues corresponding to one or more residue sets.
95

FIG. 12

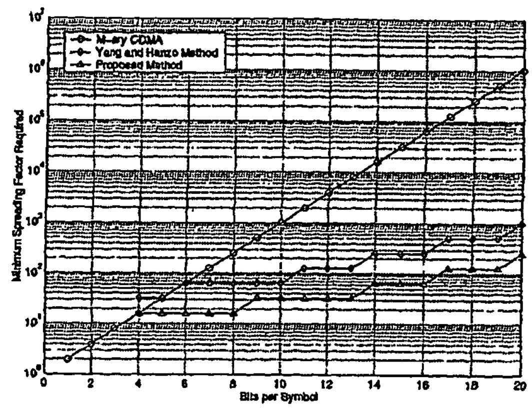

M-ary CDMA
Yang and Hanzo Method
Proposed Method
Minimum Spreading Factor Required
0
2
4
6
8
10
12
14
16
18
20
Bits per Symbol

FIG. 13

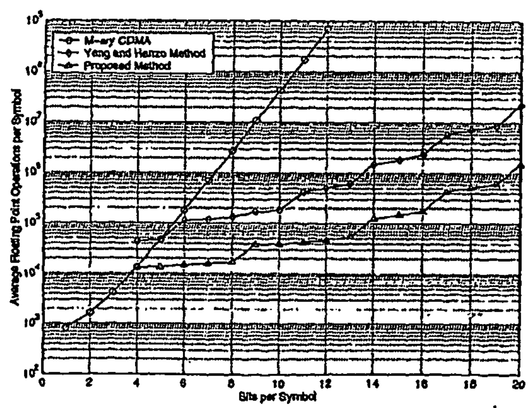

M-ary CDMA
Yang and Hanzo Method
Proposed Method
Average Floating Point Operations per Symbol
0
2
4
6
8
10
12
14
16
18
20
Bits per Symbol

FIG. 14

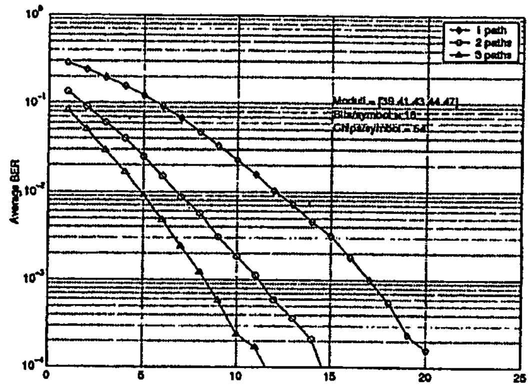


FIG. 15(a)

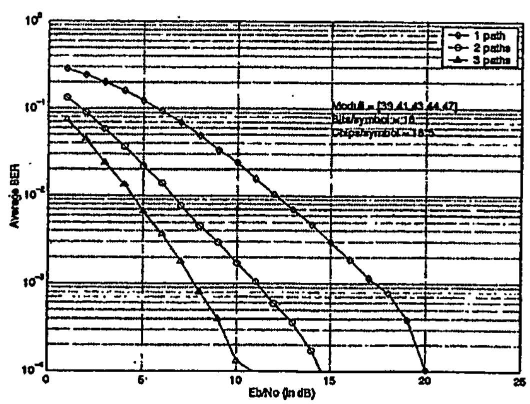


FIG. 15(b)

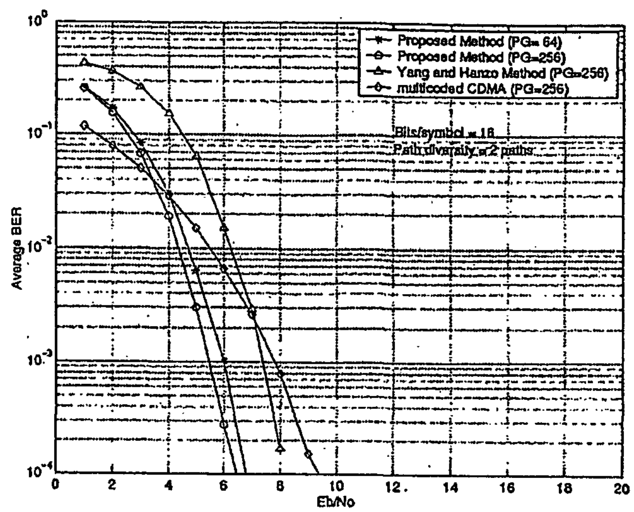

Proposed Method (PG=64)
Proposed Method (PG=256)
Yang and Hanzo Method (PG=256)
multicoded CDMA (PG=256)
Bits/symbol = 16
Path diversity = 2 paths
Average BER
Eb/No

FIG. 16

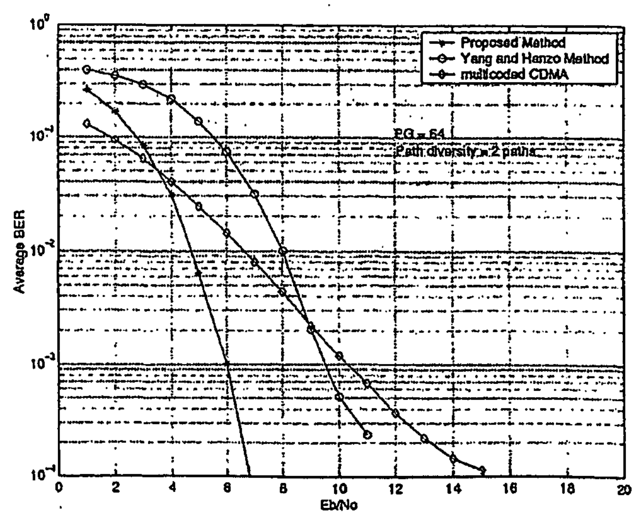

Proposed Method
Yang and Hanzo Method
multicoded CDMA
PG = 64
Path diversity = 2 paths
Average BER
Eb/No

FIG. 17

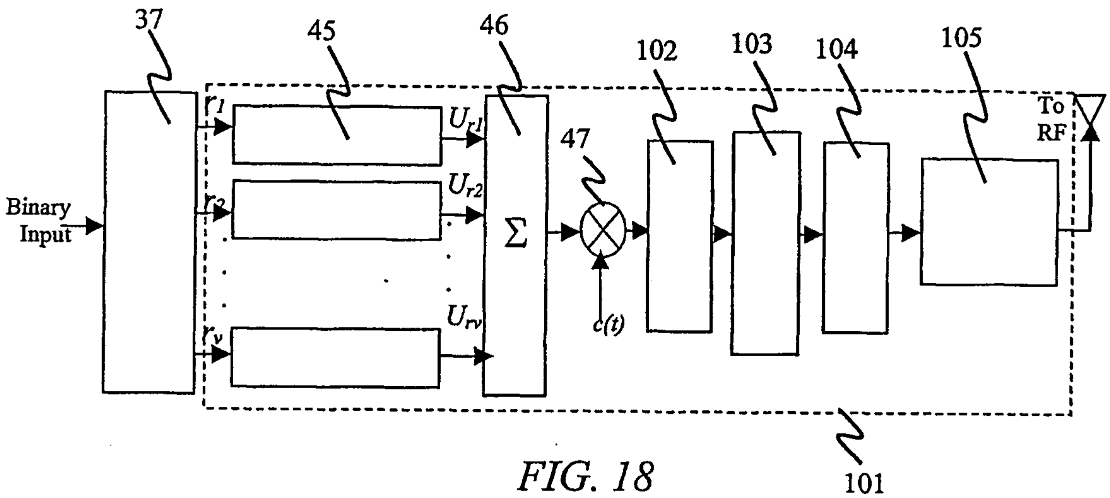


FIG. 18

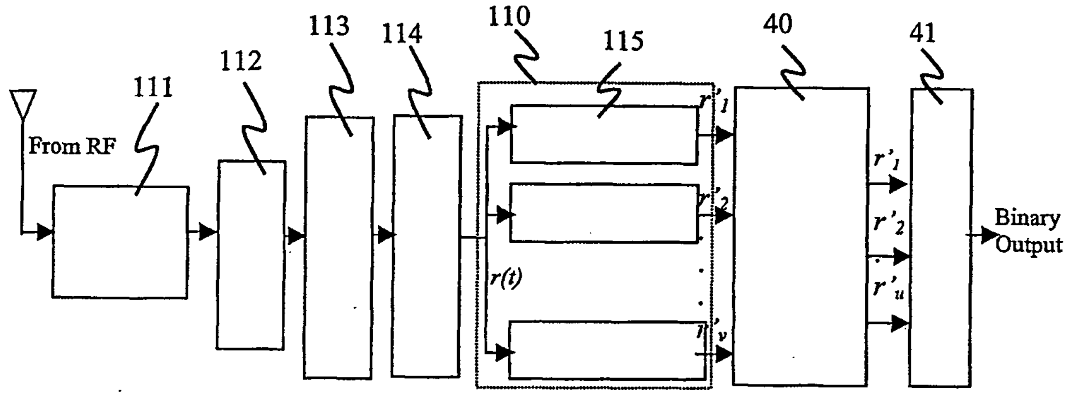


FIG. 19

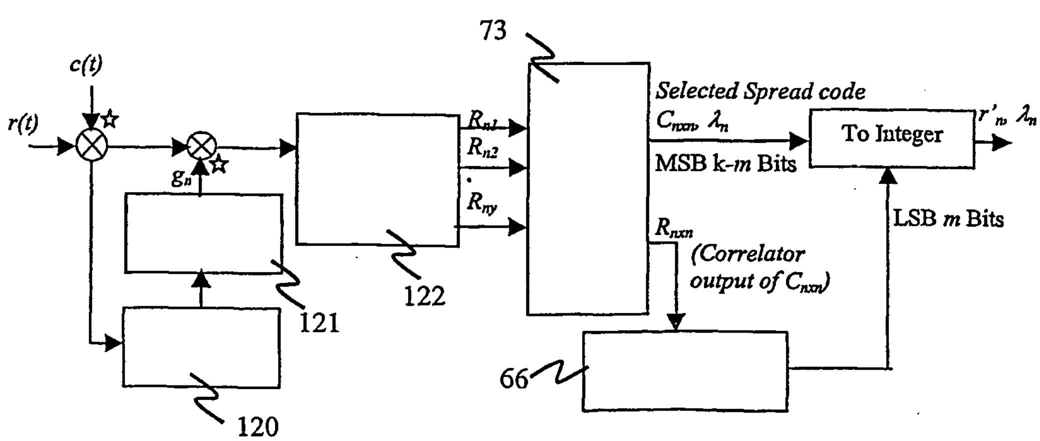


FIG. 20

INTERNATIONAL SEARCH REPORT

International application No.
PCT/SG 01/00011

CLASSIFICATION OF SUBJECT MATTER

IPC^7: H04B 1/69, 7/216, H04L 27/26

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC^7: H04B 1/69, 1/707, 7/216, 7/26, H04L 7/00, 27/26, 27/30

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

WPI

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0717520 A2 (NIPPON ELECTRIC CO.) 19 June 1996 (19.06.96) *figs. 4A, 4B; claims 1,7,16-18.*	1,14,26,39
A	EP 0729241 A2 (AT&T CORP.) 28 August 1996 (28.08.96) *figs. 2,3; claims 1,7,17,21.*	1,14,26,39

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents:
„A" document defining the general state of the art which is not considered to be of particular relevance
„E" earlier application or patent but published on or after the international filing date
„L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
„O" document referring to an oral disclosure, use, exhibition or other means
„P" document published prior to the international filing date but later than the priority date claimed

„T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
„X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
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Date of the actual completion of the international search	Date of mailing of the international search report
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INTERNATIONAL SEARCH REPORT
Information on patent family members

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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP A 0717520		none	
EP A 0729241		none	